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IONOSPHERIC MODIFICATION BY HIGH POWER, OBLIQUELY PROPAGATED HF RADIO WAVE TRANSMISSIONS PART 1: EXPERIMENTAL

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Published material on heating of electrons in the ionosphere using high power transmissions at high frequencies typically used for communications and OTH radar systems, is reviewed. Although the emphasis of the reviewed experimental papers involves the oblique nature of the radio transmissions, actually the important factor that differentiates these measurements from typical high power plasma heating studies is the fact that these involve underdense heating, i.e. at frequencies above the maximum plasma frequency in the ionosphere. The process of inclusion into this report necessitated a critical judgement of the published experimental results, requiring of them, either a degree of credibility and repeatability or when they have become part of the folk lore in the field of oblique heating. In the latter case, a critical review of the reported results is undertaken in light of current and best understanding of "heating" phenomenology.

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1.0 INTRODUCTION

This report (Part I - Experimental and Part II - Theoretical) presents a comprehensive review of both experimental and theoretical work on the modification of the ionosphere using high power HF (3 to 30 MHz) radio transmitting systems. Here only obliquely radiating systems are considered, differentiating them from systems that have been built by the scientific community since the 1960's, beginning with the Platteville, Colorado facility (Carroll, 1974; Utlaut, 1974), specifically for vertical incidence ionospheric modification and plasma research. The radio systems considered here are built for other applications and, as is often the case, their operators seek better performance by going to higher power levels and more directive antenna systems. Unfortunately, as the radiated power density increases, the operators may not achieve the expected improved performance when changes in the ionospheric medium appear that are related to the higher power density. The processes of interest here are non-linear, i.e. where the incident radio wave is sufficiently strong that it is able to modify the medium in which it is propagating and in turn the strong radio wave is itself modified by these changes in the medium and often in addition other signals are also affected as they pass through the modified region of the ionosphere.

The earliest and best known example of non-linear wave interaction was discovered by Tellegen (1933) and shortly thereafter called the Luxemburg effect or cross-modulation effect. This occurred when a strong broadcast station in Luxemburg at a frequency of 252 kHz was found to superimpose its relatively low frequency voice modulations on other low power "wanted" signals propagating across Luxemburg usually from the south into Eindhoven, Netherlands. Tellegen was reasonably certain that the disturbance was not in the receiver but somewhere in the propagation medium.

Within one year a rather correct solution to the mystery was put forth by Bailey and Martyn (1934) involving non-linear absorption though their understanding of magnetoionic theory at the time was not sufficient to correctly identify the region of the ionosphere involved in the wave interaction process.

By 1948, Ratcliffe (1948) was able to confirm the interaction altitude to be in the D and E-regions, where the absorption of these radio waves (at 167 to 1000 kHz) maximized. Experimentally, they were able to estimate the electron - neutral collision frequency at 85 km from their experiments. This was the beginning of a long series of interaction experiments for the study of the D-region that are not directly relevant to this report.

Of particular interest in this review is the situation where the frequency of the disturbing transmitter is greater than the plasma frequency in the ionospheric interaction region. In fact, with many practical radio transmitting systems, the high power disturbing transmitter typically operates at a frequency 2 to 3 times the maximum plasma frequency in the ionosphere. This so-called underdense "heating" must be distinguished from the more commonly employed vertical incidence ionospheric heaters (Tromso, Norway; Arecibo, Puerto Rico, etc.) which operate so that in the interaction region the "heater" frequency matches one of the local plasma resonance frequencies.

This resonant heating, much more effectively couples the radio wave energy into the plasma and the effects on the ionosphere are often quite dramatic. These systems serve as a very effective tool for the study of plasma physics.

The subject of underdense heating is of significant practical importance, representing the situation for high power HF broadcast systems and Over-The-Horizon (OTH) radar systems. As the effective radiated power of these systems increases, the non-linear interaction with the ionospheric plasma becomes significant and potentially limits the gain that can be achieved with these higher power systems.

Vertically incident plasma resonant heaters also have to consider the effects of underdense heating especially as they move to higher power levels. For these systems the signals usually must penetrate lower lying ionization before reaching the desired interaction altitudes, usually in the F-region (300 km). In these lower regions the interaction of the heater wave is also underdense.

2.0 BACKGROUND

2.1 ITS Platteville Experiments

In the 1960's the Platteville, Colorado (40.3°N, 104.8°W) heating facility under the direction of the Institute of Telecommunications Sciences (ITS) was modified to be used for oblique heating experiments. Here the nine 200 kW transmitters were used to drive a special array of vertically polarized log-periodic transmitting antennas looking towards the east. The effective radiated power for this system was approximately 82.5 dBW. The results of these tests were negative and the effort was abandoned by 1969 (Utlaut, personal communications). As is shown later in this report, this power level was too low, requiring at least 90 dBW before the effects are detectable.

2.2 Soviet Research

2.2.1 Introduction

In the area of underdense ionospheric modification using high power oblique transmissions, Soviet theoretical and experiment publications represent some of the earliest work that followed the cross-modulation experiments. Unfortunately, the early (circa 1970 - 1980) Soviet experimental research are often anecdotal and they are not very convincing that repeatable heater induced changes were able to be observed. Often the chronology of these experiments is difficult to reconstruct and often the basics of the experimental configuration and operating parameters are missing. In contrast to this experimental work the theorists appear to be superior, clearly lead by V.L. Ginsburg and A. Gurevich. Currently, the best and most complete reference on ionospheric modification appropriate for this subject is the classical theory (non-kinetic theory) as developed by A. Gurevich and comprehensively reported in his book entitled "Nonlinear Phenomena in the Ionosphere", published in 1978 by Springer-Verlag (Gurevich, 1978).

A summary of the Soviet experimental work is presented here without attempting a strict chronological order but by dividing the work into F-region interaction and then E-region and sporadic-E effects. For good reason, the authors are not always specific about the location of the interaction region. It is not easy to determine the

altitude of the strong interaction since the radio wave penetrates several layers in the ionosphere along the path from the transmitter to the receiver.

2.2.2 F-Region Modification

Some of the earliest reported experimental works on dedicated oblique incidence heating were by the IZMIRAN (Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation) group in Moscow under the direction of G.S. Bochkarev with the strong support of Yu. N. Cherkashin. Their early work began in the 1970's using a high power transmitter, probably located in the Moscow (55.8°N, 37.6°E) area, broadcasting in a southeast direction to sites that vary in distance from 1800 km to 3600 km from the transmitter. The best version of their work in English was published in the Journal of Atmospheric and Terrestrial Physics (Bochkarev, 1982). There are several versions of this same material published in different places, including inhouse IZMIRAN reports and in Geomagnetism and Aeronomy (Bochkarev,1980) combined with other authors, but always lead by G.S. Bochkarev. As part of their program, the Soviets introduced the technique of using a low power HF probing system to measure changes in the state of the ionosphere as the high power transmitter is cycled on and off. This probe operates continuously along the same path as the high power system at essentially the same frequency (differing by a few kilohertz from the high power system to avoid having the probe receiver blocked by the high power signal).

Here, in a daytime experiment, they present a single example of the change in the amplitude of the received probe signal following the turn off of the high power transmitter. These data, reproduced here in Figure 1, includes the azimuthal and elevation arrival angle variations as well as the amplitude of the probe signal. Both angle of arrival measurements are noisy and the reported changes are relatively small (particularly for the azimuth angle, $\approx 0.1°$) and any correlation with the heater cycling is not very convincing. As is shown later in the U.S. experiments, the amplitude changes most likely occurred in the D and E-regions and the Soviet authors explanation of F-region modification by heating within the standing wave pattern of the up going and reflected waves forming horizontal striations near the reflection region, is not very credible. In their analysis they ignored both the background and modified attenuation of the heater signal as the powerful wave passes through the daytime D and E-regions causing modification and self absorption on the up leg of the high power signal on the transmission path.

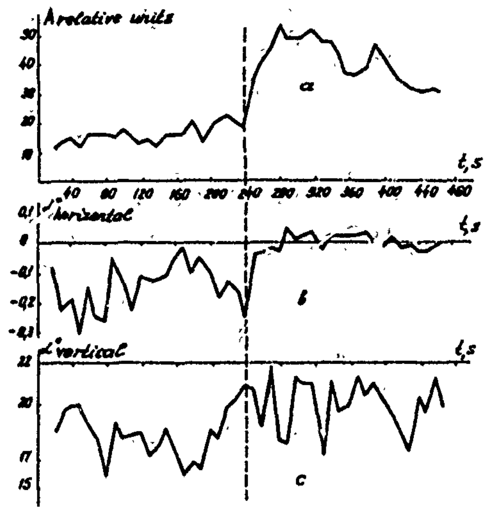

Figure 1. Amplitude, elevation and azimuth arrival angle changes that occur on a 12 MHz probe signal over an 1800 km path when a 90 dBW ERP disturbing transmitter is switched off (Bochkarev, 1982)

Although the heating frequency is not given in the referenced paper, it can be estimated from the ray tracing shown in their paper (Bochkarev, 1982, page 1139). The best estimate that can be made today for their operating frequency is 12 MHz, consistent with the frequency that produces the highest antenna gain for the U.S. ionospheric modification experiments using an antenna similar to the large Voice of America (VOA) transmitting array discussed below. Although the effective radiated power level of the high power transmitting system is not provided in this paper it can be estimated by analysis and through private communication with the authors that their system was about the same as the Voice of America system, i.e. 90 dBW.

At the URSI meetings held in Suzdal in Sept. 1991, Bochkarev presented a definitive summary paper (referenced as Suzdal 91-1 and included in the Abstracts of that meeting along with the outlines of several other works that involved other institutions besides IZMIRAN). In Suzdal 91-1, Bochkarev discusses, among other matters, the details of his 1976 experiments discussed above. He states that the effective radiated power of the powerful transmitter is 0.5×10^9 W, very close to the best levels achieved during the USAF VOA experiments.

He also revealed for the first time in this review paper, new experiments carried out in the summers of 1987 and 1988 involving a receiving system aboard a research vessel in the north Atlantic and high power transmitting sites in Moscow and Nikolaev (46.95°N, 32.0°E, near Odessa on the Black Sea). These oblique paths varied, in ground distance, from 1700 km to 3100 km. In this note, they state explicitly that the heater frequency was 12 MHz as was deduced from the ray tracing in the earlier paper. The most probable location for the receiving ship during these experiments was in the region north of Iceland.

The identified changes in the probe signals were determined by the method of superimposed epoch after averaging over each one minute of data, first for five minutes during the on-period of the heater and then for five minutes after the heater was turned off. The mean level for the entire five minute period of transmitter on and off were also determined. Two examples are shown in the Suzdal abstracts, the first where the heater power is reduced from full to ten percent of full power and the mean signal level increases by 20% and the second example, where the heater is only reduced to 25% of full power and the mean signal increase is described as less that 10%. The important statement made by Bochkarev in his review, in terms of the proposed theory that the lower ionosphere is involved in the heating process, was that in 60 to 85% of the cases the probe signal decreased with the turn-on of the heater transmitter.

Their proposed explanation again involves the formation of F-region irregularities as evidenced in the oblique ionograms made at the same time. The details of the oblique ionogram soundings over the same path are described in the Suzdal Abstracts (1991, 91-1 and 91-2). These ionograms were made over the frequency range from 3.5 to 27.5 MHz once every 12 minutes.

Analysis of these oblique ionograms in terms of the variations of MOF's and LOF's for the E, Es, F1 and F2 modes are presented for the experiment on 4 Sept. 1987 from 0830 to 1200 LT on a magnetically quiet day. The operating frequency varied from 0.68 to 0.80 of the MUFF2. For this experiment the heater was turned on at 0900 LT and kept on continuously until noon. Two important observations were made during this experiment. First, they report that the Es mode disappears at 1030

LT and returns around 1100 LT and, second, they see periodic variations (approximately one hour period) in LOFF2 (lowest observable frequency) with an amplitude of about ± 2.5 MHz. Contrary to their conclusions, these observations may again indicate modification of the D and E-regions, rather than in the F-layer. Heating in the lower ionosphere affects the wave absorption and the LOF much more than the MOF (maximum observed frequency), which they report, was little affected.

In the summer of 1989, research groups from Moscow and N. Novgorod conducted propagation experiments using the high power Moscow transmitter on a 2000 km path directed slightly southeast over Kaliningrad (55° N, 20°E) located near the midpoint of the path (Bochkarev, 1991). A vertical sounder was located at Kaliningrad. They observed additional F1 traces and "hooks" moving up on the regular overhead traces; opposite to the usual downward motion produced by passing TID's. During these experiments the heater frequency was chosen so that the vertical signal was reflected in the F1-layer.

Other experiments discussed in this review paper were operated towards the west from Moscow to Tomsk (56.5°N, 85.1°E) in 1985 and 1987. Variable Doppler shifts of the order of 0.3 to 0.4 Hz were observed on the probe signal with mean periods of the order of 20 minutes. Figures 4 and 5 of their report are reproduced here as Figure 2. Details of this work are reported in IZMIRAN Report #1 (Bochkarev, 1988), entitled "Experimental study of powerful oblique radiation effects on the spectral frequency characteristics of oblique probe signals" which was translated for this synoptic study. Bochkarev also discusses the appearance of "new" modes when the powerful transmitter is turned on. These observed variations of Doppler frequency shifts were observed all the time in the USAF VOA experiments and have been interpreted as the normal variations in the ionospheric paths. The USAF experiments also observed the appearance of new modes which are interpreted in terms of seeing much weaker, high ray modes, though relatively infrequently compared to the consistent low ray modes and it was not possible to correlate their occurrence with the heater operations.

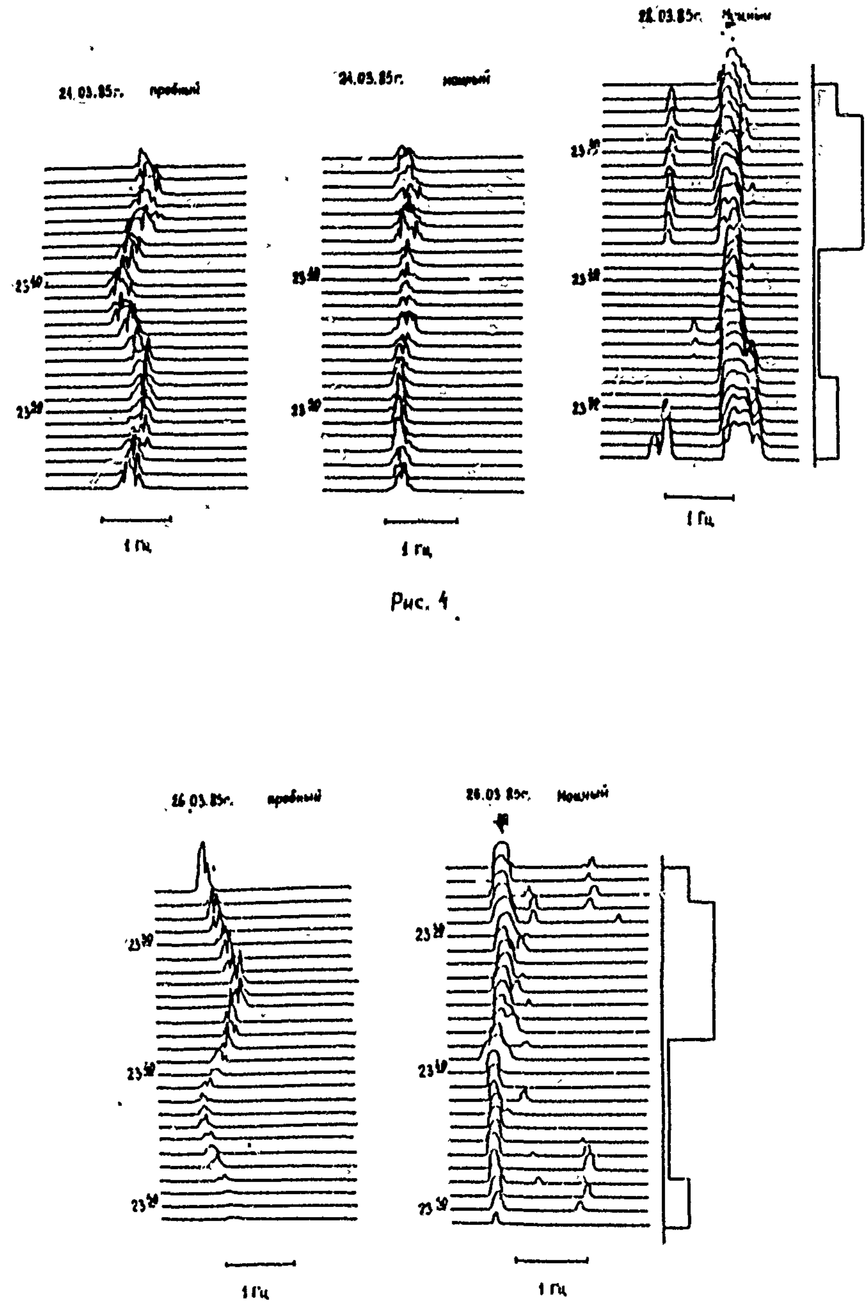

Figure 2. Doppler frequency variations and mode structure of the probe signal over a path from Moscow to Tomsk as the disturbing transmitter is switched on and off (Bochkarev, 1988)

Two other papers appear in the Soviet literature by a different group of authors with unspecified affiliation, with the V.I. Novozhilov as the common author. These two papers appeared as a pair in Geomagnetism and Aeronomy. The first paper (Krokhmal'nikov, 1978) discusses changes in the differential frequency, when the oblique heater is turned on, between the high ray and the low ray signals over a 3000 km path where the oblique heater and the probe are operating at ≈ 0.9 x MUF. In these experiments the powerful transmitter achieved field strengths in the F-region of the order of 0.1 x E_p, where E_p is the characteristic field as defined by Gurevich (see Part II for more detail). These data were taken in April, 1975 at 1400 to 1600 LT on an east to west path somewhere in the Soviet Union. They invoke a theory that there is a different behavior when heating the lower F-region where the electron density increases while at the same time heating above 250 km decreases the local electron density. This is interpreted by the authors as generating the differential effect. These data are reproduced in Figure 3 where three 15 minute heating cycles are shown with the concurrent increases in the differential Doppler, reaching values of 0.1 to 0.15 Hz compared to the background variations (no heater) of the order of less than 0.02 Hz. Each measured point represents an average over a two minute period. These observations are convincing, however, the authors do not explain how the heating process extends over such a large altitude range in the F-region. *Any* heating in the underdense situation in the F-region is difficult to achieve as was indicated earlier and is discussed in detail in Part II.

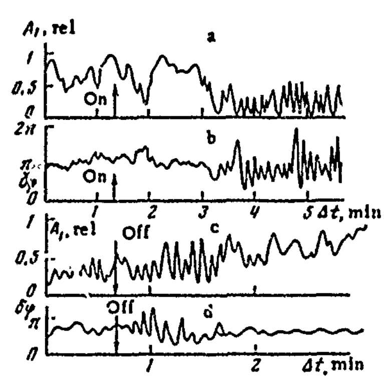

Figure 3. Changes in the character of the amplitude and phase fading as a disturbing transmitter is turned on and off (Novozhilov, 1978)

The second paper (Novozhilov, 1978) discusses amplitude changes during the same experiments as in the first paper. In this case, the probe signal traversed the 3000 km path in a direction opposite to the heater signal though this should be of little consequence. Basically, they observed an increase in the phase and amplitude fading rates some two minutes after the heater was turned on and a decrease in these fading rates some 2 minutes after the heater was turned off. In these experiments they operated the heater and the probe transmitters at 0.9 to 0.96 x MUF and both the high and low ray modes were present at the time. These measurements did not separate the high and low rays and the observed fading rate changes are likely related to the interference between the two Doppler frequency shifted modes. The authors point to the self-focusing instability (see Part II) as the source of the F-region irregularities.

2.2.3 E-Region Modification

Two papers were published in 1977 (Kozlov, 1977a,b) describing a series of oblique heating experiments in May through July 1974. All these measurements were taken between 0830 and 1100 Moscow time using an oblique "sounder" capable of producing a ratio of field strength to characteristic plasma field in the E-layer of 0.2 to 0.3. Unfortunately no information on the operating parameters of the heating system concerning frequency, antenna gain or elevation angle are provided making it difficult to compare these experiments with the USAF VOA experiments discussed in Section 2.4.

At oblique incidence ($\approx$ 15° elevation angle), the 90 dBW, VOA Delano facility produced a field strength of approximately 0.4 V/m at 12 MHz at 100 km altitude at night, when there is no absorption of the heater signal passing through the D-region. Similar to the Kozlov experiments, the VOA Delano experiments using a standard atmospheric model for temperature and density, find the ratio $E_o/E_p \approx 0.3$. In computing the local field strength in the E-region, Kozlov considered only the free space losses and ignored D-region absorption, modified or unmodified, in spite of the fact that they ran daytime experiments.

The Soviet experiments ran for a total of 18 hours over six different days from 16 May through 23 July, 1974. A vertical incidence ionosonde was used to measure the critical frequency of the sporadic-E layer (f_oE_s) and the blanketing frequency of the layer (f_bE_s). Actually, the two values followed each other very closely and only f_bE_s

is discussed here. On four of the six days f_bE_s and f_oE_s were generally less than or equal to 4 MHz and the authors did not recognize any changes that correlated with the heater on/off cycling. The heater was turned on during these experiments for varying lengths of time, from 5 minutes to 80 minutes.

On two days when the Es layer was rather intense, reaching as high as 8 MHz during the test period, changes did occur that appear to correlate well with the heater cycling. The authors ignored, for unspecified reasons, the event on 12 June when the f_bE_s increased abruptly when the heater was turned on and decreased again when the heater was turned off some 30 minutes later. On 23 July, the event they did recognize and use as the basis of the second paper, was one where f_bE_s decreased when the heater was turned on and increased again when it was turned off. The changes in both of these examples were in the order of 3 MHz, i.e. from 5 MHz to 8 MHz on 23 July and vice versa on 12 June.

One peculiarity of the 23 July event was that no change in the Es layer was observed for the first ten minutes of heating. Kozlov hypothesizes that the heater antenna may not have been properly directed or it took that long for the heater to reach full power.

In their second paper, the authors analyzed these experiments using a wind shear model of Es layer formation including metallic ions. The relevant theoretical (Ignat'yeva, 1976) appeared in the literature approximately two years after these experiments but one year before Kozlov published his results on the effect of strong radio waves on the formation of E_s. The work by Ignat'yeva represents a significant effort to simulate the effects of high power HF electromagnetic waves on the formation of E_s, including the chemistry of positive metallic ions as well as the dominant NO^+ and O_2^+ ions and ambipolar diffusion. The theory concludes that ohmic heating decreases the maximum electron density in the Es layer while increasing the thickness of the layer, likely, only representing a redistribution of the heated electrons. Figure 4 shows the changes in the electron density, as a function of altitude, when the heater increased the electron temperature by a factor of two over the ambient temperature. This work is reported in more detail in Part II on the theory of ionospheric modification. The Ignat'yeva paper is not concerned with the mechanisms for heating the electrons.

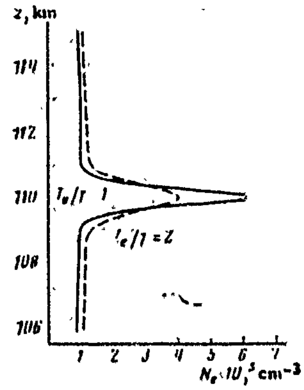

Figure 4. Modification of the electron density distribution in a sporadic-E layer when the ambient electron temperature is increased by a factor of two (Ignat'yeva, 1976).

In the Kozlov paper, the change in the electron temperature is determined from the change in the critical frequency of the Es layer (Figure 5) after heating for about 40 minutes. Kozlov estimated that, as an upper limit, Te/T ≈ 12 to 17 and the time constant associated with this temperature change is very short. The relatively slow changes in the character of the Es layer that they report, occur by modification of the chemistry and diffusion processes. Basically they show that good agreement is achieved with this model using an ambipolar diffusion coefficient $D_a \approx 10^6$ cm^2/s. This leads to a recovery time in the order of 30 minutes. This must represent the time it takes for the Es layer to reform after the heater is turned off. The subject of Es layer heating is discussed below as part of the explanation of the USAF VOA experiments.

2.3 Early US Air Force Experiments

2.3.1 Tullahoma Experiments

The first US oblique heating experiments after the Platteville tests were conducted by the USAF Rome Air Development Center (RADC) in May, 1984. These experiments used the RADC high power transmitting facility at Ava, New York (43.5°N, 75.3°W). The heating transmitter had a maximum power of 300 kW feeding a large horizontal rhombic antenna. The ERP for this system was

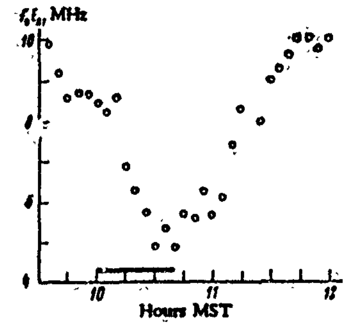

Figure 5: Time variation of the critical frequency of a sporadic-E layer during a heating experiment (Kozlov, 1977).

approximately 75 dBW, well below the level required for detection of heater effects, although this was not understood at the time. A vertical sounder located approximately 1300 km southwest of the transmitter at Tullahoma, Tennessee (35.4°N, 86.2°W), was used to detect changes in the F-region.

These experiments were carried out at night and a vertical sounder (Digisonde), built and operated by the Center for Atmospheric Research at the University of Lowell, Lowell, MA. (now the University of Massachusetts Lowell) was located at Tullahoma. The routine mode of operation of the sounder system during these experiments was first to provide a relatively short ionogram for frequency management purposes, that is, to insure that the caustic focusing region at F-layer reflection heights near the midpoint of the path lies in the vicinity of the Tullahoma site. As is shown later in Part II, the maximum F-region heating occurs within the caustic region because of the enhanced electric field intensity that occurs there. The ground end of this path (2600 km from Ava, NY) lay in the Gulf of Mexico and it was not possible to use an oblique probe system similar to the technique used by the Soviets in their experiments. In between the vertical soundings, the Digisonde operated in a fixed frequency drift mode and these data were analyzed for periodic phase changes that might correlate with the heater transmitter on/off cycling with a 10 minute period.

Extensive statistical analyses (Sales, 1986) were carried out in an attempt to detect phase changes that correlated with the heater cycling without any success. The analysis did produce a median spectrum of naturally occurring phase fluctuations which were useful for future experimental planning. Figure 6 shows a composite periodogram for the nighttime data and illustrates how the noise power (natural phase fluctuations) decreases at the shorter periods and how considerable signal to noise gain can be achieved using heating periods less than 10 minutes. Concurrently with this analysis, E. Field (1985) and associates were carrying out the theoretical analysis of heating in the F-region and it was quickly determined that the power level in these Tullahoma experiments was too low to achieve detectable heating and the primary benefit derived from these experiments was the technical experience of managing the system and methods of analysis developed here that would be of use in future heating experiments.

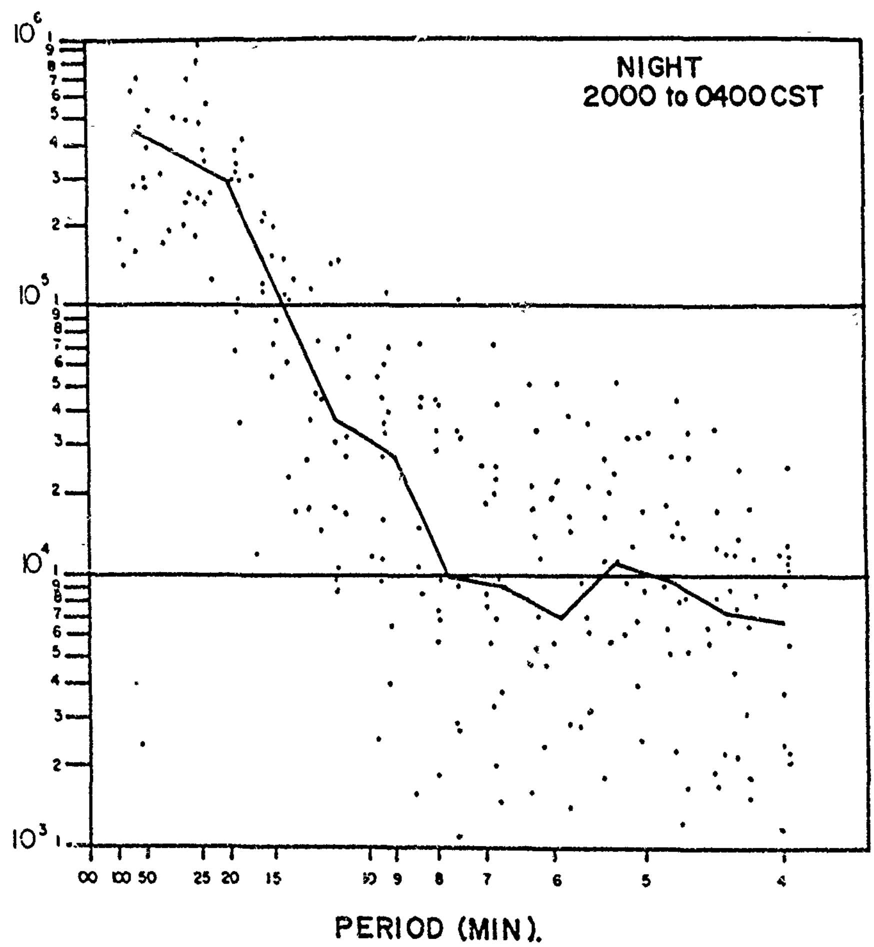

Figure 6. Spectrum of natural phase fluctuations at night measured using the vertical incidence soundings at Tullahoma, Tenn. during a series of heating experiments (Sales, 1986).

2.3.2 ECRS Experiments

Following the Tullahoma experiment, the USAF decided to try again with higher transmitter power using the Over-the-Horizon radar system located in the state of Maine near Bangor (44.8°N, 68.7°W). This system has an ERP = 84 dBW with an azimuthal beamwidth of 7.5° and was steered, putting the full power in the direction of Argentia, New Foundland, Canada (47.3°N, 54.0°W) a distance of approximately 1200 km from the transmitter. Again the operating frequency was selected to place the F-region caustic focusing area over the Argentia vertical sounder. The radar system uses a FMCW wave form with a bandwidth of 10 kHz about any carrier frequency between 5 and 28 MHz. The Air Weather Service vertical sounder at Argentia was used for frequency management and for detection of changes in the F-region as the heater power was cycled with a 10 minute period. Again it was impossible to employ a probe technique since the far end of the path (2400 km from the radar) was out in the Atlantic ocean.

In spite of the fact that the ERP was increased by about 10 dBW over the Tullahoma experiments, the power was still approximately 6 dB below the 90 dBW used in the Soviet experiments. This makes the detection of heater induced changes very difficult. Combined with a relatively disturbed ionosphere at the relatively high latitudes near the auroral region probably contributed to the negative results of this series of experiments.

2.4 Voice of America (VOA) Experiments

2.4.1 VOA Delano Transmitting Facility

This series of experiments were initiated because the VOA broadcasting system located at the Delano Relay Facility in Delano, California (35.8°N, 119.2°W) was able to provide the highest ERP in the United States, comparable with the best estimate of the power levels achieved by the earlier Soviet experiments.

The Delano antenna system, boresited at 105°T, consists of two 2-D vertical phased broadband dipoles arrays, one for frequencies from 6 to 12 MHz (low band array) and the other (high band array) for 13 to 26 MHz. The gain of each of these arrays varies with frequency from about 24 dB at the low end of each band to 30 dB at the high end, i.e. at 12 MHz and 26 MHz, respectively. Each of these arrays is constructed

with three bays, each bay consisting of 24 elements, 4 elements wide by 6 elements high, for a total of 72 elements. At the beginning of this series of experiments only a single feed line was available so that only one transmitter, with a modulated output power of 375 kW, was able to be connected to the array. This limited the ERP to about 86 dBW. In order to achieve the full potential of the VOA facility, the USAF provided the funds to construct two additional feed lines so that it became possible to connect three transmitters, one to each of the three bays that make up each array.

Each transmitter had a nominal power level of 250 kW and was modulated at close to 85% at a relatively low frequency so that the total output power was 375 kW for each transmitter. At 12 MHz, with all three transmitters, properly phased, combined with the antenna gain, represents a 90 dBW ERP system.

2.4.2 Low Power HF Probe System

Following some of the Soviet publications where they describe an HF probe system for detecting heating changes (Bochkarev, 1982) a similar system was built by University of Massachusetts Lowell, Center for Atmospheric Research (ULCAR). The transmitting portion of the probe system (500 W, continuous) was colocated with the high power heater facility and was designed to transmit over an oblique path at essentially the same frequency as the heater transmitter. The receiving end of the system was located down range at Shreveport, Louisiana (32.5°N, 93.8°W) near the skip distance for the operational frequency. For this arrangement, with a fixed path, the operational frequency of the high power heater and the probe system must be varied as the critical frequency of the F-layer changes. The state of the F-layer was continuously monitored using a vertical incidence sounder at Albuquerque, New Mexico (35.1°N, 106.8°W) at the midpoint of the 2400 km path. This technique insures that the probe signal follows the same path as the heater and passes through the caustic region where the ionospheric disturbance was expected. Details of the system can be found in a report by Sales (1990). The primary feature of the probe system is that it transmits continuously while the high power heater transmitter is cycled on and off. The measurements made on the probe system include the amplitude, instantaneous frequency and arrival angles (azimuth and elevation) of the received radio wave, measured every 15 s.

2.4.3 Phase I Experiments

These first experiments began in Jan. 1990, before the two additional feed lines were available and were designed as a shake down test of the probe system and to aid in the development of the data processing software. With a maximum ERP of 86 dBW, no detectable modification was expected or found, though these experiments did yield a considerable amount of background data, useful in the future experiments.

The probe system is a continuous wave system and mode resolution is achieved by Fourier spectrum processing of the signal received on each antenna. Often two spectrum peaks were observed on the processed output of each antenna and associated with the high and low rays propagating to Shreveport at a frequency near the MUF for that path. The amplitude of the received signal, always for the low ray, was the power of that spectrum line and the arrival angles for the two modes was determined by comparing the phase of the same spectrum line on each of the three antenna arranged in an "L" configuration.

The time variations of these measured quantities are then compared to the heater transmitter on/off cycling, attempting to recognize a correlated variation.

2.4.4 Phase II Experiments

With the completion of the two additional transmitter feed lines and the transmitter phasing measurements (made by VOA) on the three independent transmitters, it was decided to begin full power experiments. The proper phasing of the three transmitters was a critical part of this effort and the phase differences were determined by measurements on the transmitted HF signal on the ground at a relatively short distance (≈ 4 km) in front of the array. These measured phase differences were then used to determine phase corrections that were"dialed" in using a phase shifter on the two outer bays relative to the center bay which was used as the reference.

At the beginning of these experiments, tests were run by operating first with one transmitter, then two and finally with all three transmitters. After repeated trials, it quickly became apparent that something was wrong and the measured probe received amplitude level via the skywave to Shreveport did not change in

proportion to the number of operating transmitters. After much analysis, it was decided that the VOA phasing technique was flawed and the transmitted power levels never were able to reach the 90 dBW level and the ionospheric modification was not likely to be detected.

Following these tests a better phasing method was developed by J. Heckscher of the USAF Phillips Laboratory and some preliminary tests were carried out prior to the next set of measurements to insure that the three transmitters were properly phased.

2.4.5 Phase III Experiments

The third in this series of experiments was conducted in May and June, 1991 after the efficacy of the new technique for phasing the three 375 kW transmitters providing the maximum radiated signal was confirmed. These experiments were carried out primarily at night, as were all the previous ones because, as is shown later, the use of lower heating frequencies increases the potential for greater change in the electron temperature. Again, the selected frequency was 12 MHz to take advantage of the maximum transmitting antenna gain using the low frequency array The heater was routinely operated on a five minute on/five minute off cycling period. The detailed results of these experiments are reported by Sales (1992) and only a brief synopsis is included here to complete the historical sequence.

Here for the first time the US program detected changes in the ionosphere that are attributable to the high power heater transmitter. These experiments were run on five successive nights from about 2100 LT to 0200 LT. While the probe system ran at the heater frequency over the 2400 km path, the ULCAR Digisonde was operated at the midpoint site for frequency management and ionospheric characterization. For four intervals of approximately one hour each (approximately four to six 10 minute heating cycles) on different nights, changes in the amplitude of the received probe signal were recorded that correlated very well with the cycling of the high power heating system.

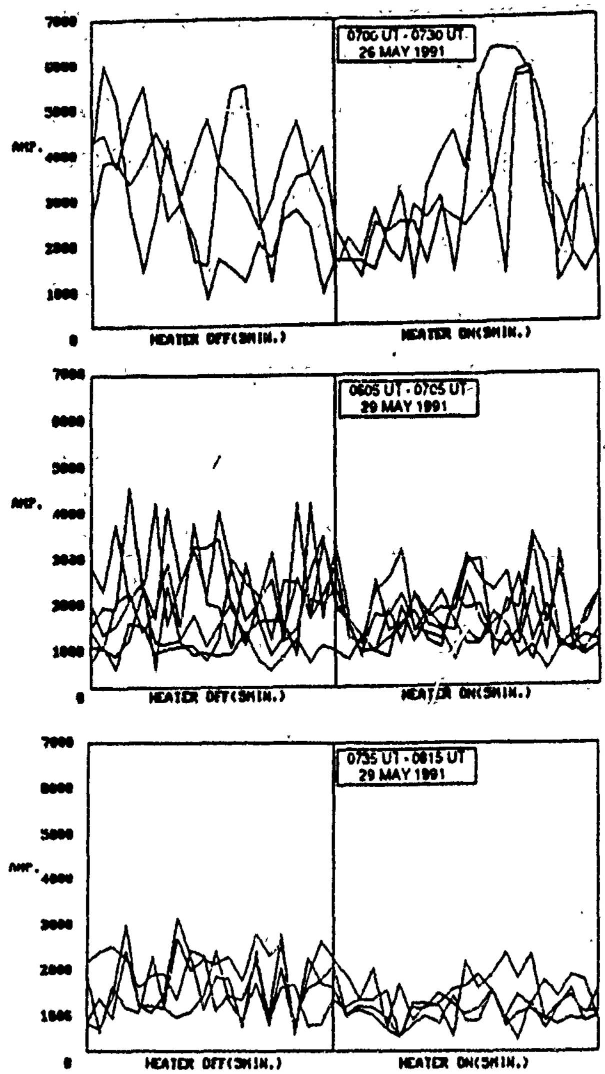

Figure 7. Spectrum of natural phase fluctuations at night measured using the vertical incidence soundings at Tullahoma, Tenn. during a series of heating experiments (Sales, 1986).

For these events, using the method of superimposed epoch, a sample of which is illustrated in Figure 7, the probe signal amplitude was observed to decreased between 2 to 3 dB, commencing essentially at the heater turn on and reversing at transmitter turn off. The time constant associated with these changes was shorter than the 15 s time resolution of the measuring system and as shown in Part II in the theory, inconsistent with the relatively long time constants (of the order of 10^3 s) associated with F-region modification. Another important observation was that no

changes in the arrival angles of the signal were observed that correlate with the heater cycling at the same times as these amplitude changes occurred. This again speaks against F-region modification. Any significant modification of F-region electron density should change the refractive index and the ray angles. The lack of any angle changes is in essential agreement with Bochkarev's results where the changes in arrival angles described, not very convincingly, by Bochkarev were of the order of 0.1°.

During these US experiments, in summertime, considerable Es was present as measured at the midpoint vertical ionosonde and it is reasonably argued that the high power transmitter was able to heat the concentrated electrons within this thin layer and increasing, very quickly, the electron neutral collision frequency (the time constant for modifying the collision frequency in the E-region is in the order of $\approx 10^{-3}$ s), thereby increasing the absorption of the heater wave and the probe wave passing through the heated Es region. In these short times, little change in the ambient electron density is expected.

3.0 CONCLUSIONS

Historically, ohmic heating of the ionosphere at frequencies well above the maximum plasma frequency has turned out to be a difficult endeavor, using the best available transmitting systems which currently reach a maximum of around 90 dBW. The Soviet results are very typically, anecdotal in nature, with conclusions often based on single examples and often ignoring contrary observations without any explanation. Part of the problem in reproducing their observations is their lack of understanding of the likely mechanisms involved in the heating process. This may be a classical example of anticipated expectations driving the reported results.
These difficulties can be removed as theory improves, particularly if the theory continues to support the idea that the dominant effect lies in the E-region at night, particularly when Es is present, but even when there is no Es. The nighttime E-layer (foE $\approx$ 0.6 MHz) is a potential source of anomalous absorption at sufficiently high radiated power levels.

This situation can become a significant problem when higher power systems become available, whether these systems operate at either vertical or oblique incidence. At night, the E-region is certainly underdense in terms of the likely heating frequencies, around 4 to 6 MHz at vertical incidence. At vertical incidence, the power density on the E-layer also increases since the path length to the ionosphere becomes very short, in the order of 100 km instead of the 400 to 800 km associated with oblique propagation to the same altitude regime.

Definitive experiments should be performed in light of the improved theoretical understanding of the relevant processes. Only then can these effects be confirmed and then extrapolated to future systems.

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